Disentangling objects' contextual associations from perceptual and conceptual attributes using time-resolved neural decoding

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Abstract

Humans effortlessly relate what they see to what they know, drawing on existing knowledge of objects' perceptual, conceptual, and contextual attributes while searching for and recognising objects. While prior studies have investigated the temporal dynamics of perceptual and conceptual object properties in the neural signal, it remains unclear whether and when contextual associations are uniquely represented. In this study, we used representational similarity analysis on electroencephalography (EEG) data to explore how the brain processes the perceptual, conceptual, and contextual dimensions of object knowledge over time. Using human similarity judgments of 190 naturalistic object concepts presented as either as images or words, we constructed separate behavioural models of objects' perceptual, conceptual, and contextual properties. We correlated these models with neural patterns from two EEG datasets, one publicly available and one newly collected, both recorded while participants passively viewed the same object stimuli. Across both datasets, we found that perceptual features dominated the early EEG response to object images, while conceptual features emerged later. Contextual associations were also reflected in neural patterns, but their explanatory power largely overlapped with that of conceptual models, suggesting limited unique representation of objects' contextual attributes under passive viewing conditions. These results highlight the brain's integration of perceptual and conceptual information when processing visual objects. By combining high temporal resolution EEG with behaviourally derived models, this study advances our understanding of how distinct dimensions of object knowledge are encoded in the human brain.

Relating what we see to what we know is an essential cognitive function for humans, enabling us to draw on prior experience to successfully detect, recognise and interact with objects in the world. Doing so requires rapid and reliable evaluation of the similarity between incoming sensory information and stored representations (Clarke & Tyler, 2015; Edelman, 1998; Kok, Brouwer, van Gerven, & de Lange, 2013; Nosofsky, 1986). Despite its ubiquity, this process of comparison is inherently complex, as objects themselves are defined by a myriad of both observable visual properties (*e.g.,* colour, surface, texture, global shape, etc.) and more abstract, conceptual attributes (*e.g.,* biological status, action affordances, abstract qualities) (Clarke, Taylor, Devereux, Randall, & Tyler, 2012; Clarke & Tyler, 2015; Grootswagers, Robinson, Shatek, & Carlson, 2019; Hebart, Zheng, Pereira, & Baker, 2020; Teichmann, Hebart, & Baker, 2025). As such, objects can be both similar *and* different to one another, depending on the dimension under consideration. For example, an alligator and a rabbit are at once both vastly disparate – one is large, scaly, and dangerous; the other small, fluffy, and cute – and yet fundamentally similar – both animals that breathe, eat, and reproduce.

Recent largescale efforts to characterise the multidimensional nature of object representations have uncovered a host of dimensions that underlie human judgements of similarity both across (Hebart et al., 2019; Hebart et al., 2020; Teichmann et al., 2025) and within overarching object categories (Almeida et al., 2023). Findings suggest that both perceptual and conceptual attributes serve to structure object representations in the human visual system. Identified perceptual dimensions capture intrinsic properties of objects' visual appearance (*e.g.,* roundness, elongation, colour, flatness, shininess, texture), where conceptual dimensions encompass both taxonomic category (*e.g.,* animal, vehicle, plant), as well

as higher-level, semantically rich aspects of object meaning (*e.g.,* associations of value, heat, disgust). Disentangling how perceptual and conceptual object properties emerge in time-resolved M/EEG neural responses has been a focus within existing work on the temporal unfolding of visual object processing (Bankson, Hebart, Groen, & Baker, 2018; Carlson, Tovar, Alink, & Kriegeskorte, 2013; Clarke & Tyler, 2015; Contini, Wardle, & Carlson, 2017; Giari, Leonardelli, Tao, Machado, & Fairhall, 2020; Grootswagers, Robinson, Shatek, et al., 2019; Isik, Meyers, Leibo, & Poggio, 2014; Wardle, Kriegeskorte, Grootswagers, Khaligh-Razavi, & Carlson, 2016). This is important, since perceptual and conceptual object attributes often covary: Think of a spanner and a fork, which are similar in terms of not only material composition, size, and shape, but also function, affordance and taxonomic status (graspable tools). As a collective, these studies suggest that perceptual features give rise to early, stimulus-locked activity patterns – reflecting rapid encoding of objects' visual features – where representations of conceptual properties tend to emerge comparatively later in the neural time course, suggesting a temporal cascade from early perceptual analysis to later semantic integration (Bankson et al., 2018; Carlson et al., 2013; Clarke & Tyler, 2015; Grootswagers, Robinson, Shatek, et al., 2019; Proklova, Kaiser, & Peelen, 2019; Teichmann et al., 2025). Notably, neural representations of conceptual features also show greater variability across individuals, potentially reflecting differences in experience, familiarity, or conceptual organisation (Teichmann et al., 2025).

In addition to their inherent perceptual and conceptual features, object knowledge also comprises contextual attributes, defined by objects' predictable associations with certain environments (*e.g.,* a toothbrush in a bathroom, a knife on a countertop). A wealth of prior work has shown that contextual associations between

objects and surrounding scenes influence how we search for and recognise objects (Bar, 2004; Biederman, Glass, & Stacy, 1973; Davenport & Potter, 2004; Ganis & Kutas, 2003; Oliva & Torralba, 2007; Võ, Boettcher, & Draschkow, 2019), with scene context even serving to disambiguate neural representations for degraded objects that are otherwise unrecognisable (Brandman & Peelen, 2017; Wischnewski & Peelen, 2021). Context-based facilitation also arises at the inter-object level, with observers recognising objects more efficiently when they are contextualised by second, related object (Auckland, Cave, & Donnelly, 2007; Bar & Ullman, 1996; Davenport, 2007; Green & Hummel, 2006; Kaiser, Quek, Cichy, & Peelen, 2019; Kaiser, Stein, & Peelen, 2014; Quek, Theodorou, & Peelen, in press). Moreover, violating canonical contextual associations appears to drives reliable neural signals even when observers are not explicitly attending to congruity between the elements (Mudrik, Lamy, & Deouell, 2010; Mudrik, Shalgi, Lamy, & Deouell, 2014; Quek & Peelen, 2020), suggesting that representations of contextual object attributes may be evoked automatically during object processing.

Where prior work characterising the neural timecourse of individual object dimensions does encompass aspects of objects' contextual attributes (e.g., 'outdoors-related', 'bathroom-/wetness related', Hebart et al., 2023), to date no study has explicitly aimed at *dissociating* time-resolved representations of contextual object knowledge from their perceptual and conceptual counterparts. Understanding the degree of overlap in these three classes of object features is central to the interpretation of inter-object contextual facilitation effects, which are underpinned by both conceptual and contextual associations between simultaneously presented objects (e.g., *teacup* and *saucer* are both food/drink related and typically encountered in the same surrounding context). The present study addressed this gap

by examining the extent to which behaviourally-derived models encompassing objects' perceptual characteristics, conceptual attributions, and contextual associations predict unique variance in the unfolding neural response to object images reflected in EEG data.

To explore the intersection between processing of objects' contextual, perceptual, and conceptual features, we adapted the "odd-one-out" task used by Hebart et al. (2020) to capture subjective human perceptions of similarity among triplets of object concepts. However, rather than eliciting purely intuitive judgements of object similarity, here we imposed specific task instructions designed to result in dynamic reweighting of individual object dimensions: Different groups of online observers made triplet similarity judgements for the same 190 object concepts in terms of *i)* objects' observable perceptual properties (*e.g.,* size, colour, shape, etc.), *ii)* their conceptual attributes (*e.g.,* function, use, affordance), or *iii)* their contextual associations (*e.g.,* where the object would likely be found). Our overarching goal was to examine the degree to which each of these behaviourally-derived object similarity models would explain unique variance in the dynamically evolving representational structure of visual object processing. To this end, we correlated our object similarity models with two high temporal resolution EEG datasets recorded in separate participant samples viewing the same object images under orthogonal task conditions. These included both a pre-existing, publically available EEG dataset (referred to as "Fast EEG"; Grootswagers, Zhou, Robinson, Hebart, & Carlson, 2022) and a newly acquired dataset (referred to as "Slow EEG"), which differed in presentation rate and the number of object image repetitions.

Secondarily, we also aimed to investigate how different presentation modalities would differentially capture subjective similarity between objects'

perceptual, conceptual, and contextual dimensions. Thus, we derived separate object similarity models based on both image and label versions of our 190 object concepts. This represents a departure from previous studies that have typically modelled object dimensions based on behavioural responses to object images alone (Cichy, Kriegeskorte, Jozwik, van den Bosch, & Charest, 2019; Giari et al., 2020). Here we predicted that similarity judgments using word labels would capture object dimensions in a more abstract form, whereas judgments based on images would inherently be more visually-driven, even if participants were asked specifically to consider conceptual or contextual object properties. By using both abstractly derived (word-based models) and perceptually derived (image-based models) object dimensions to understand neural responses to objects, we aimed to further delineate the contributions of perceptual and conceptual dimensions to neural responses. Our analysis measured the degree to which the representational structure of object dimensions, as perceived by individuals, aligned with the dynamically evolving representational structure of visual object processing in the brain.

2. MATERIALS AND METHOD

The current study consisted of three parts: (1) collection of behavioural data, (2) analysis of both pre-collected EEG data ('Fast EEG') and newly acquired EEG data ('Slow EEG'), and (3) Representational Similarity Analysis using data from (1) and (2).

2.1 Stimuli

To investigate how different dimensions of human similarity judgments are reflected in the neural processing of visual objects, we took advantage of the

THINGS stimulus database (Hebart et al., 2023; Hebart et al., 2019). This open-source database consists of 1,854 object concepts systematically sampled from a wide range of concrete nouns that can be visually depicted and labelled in American English. These object concepts correspond to basic-level categories such as *dog, car, spaghetti,* and *foot*. Each concept is associated with a word label and includes exemplar images that showcase the objects embedded within naturalistic scenes. These exemplar images capture the objects in diverse colours, shapes, angles, positions, lighting conditions, and other visual characteristics, creating a rich and varied visual context for each object concept. Additionally, each concept belonged to one of the 27 high-level categories defined by THINGS, which represent broader superordinate categories such as vehicles, animals, food, and body parts (Figure 1A).

Since it was infeasible to derive six separate models for the full set of object concepts in the THINGS database, here we focused on a subset of 190 object concepts spanning the top 25 high-level categories identified in the original THINGS database (*food, animal, clothing, tool, sports equipment, vegetable, vehicle, musical instrument, fruit, body part, dessert, toy, container, part of car, weapon, bird, furniture, kitchen tool, office supply, kitchen appliance, plant, insect, home décor, medical equipment, electronic device*). From these high-level categories, we selected 7-8 concepts per category, which resulted in 190 object concepts in total, each of which was represented by 10 exemplar images and a word label. This resulted in a final stimulus set of 1900 images (used in behavioural and EEG data collection) and 190 words (used in behavioural data collection only).

2.2 Behavioural Data Collection

The goal of our behavioural data collection was to model functionally-derived similarity in our set of 190 objects' perceptual, conceptual, and contextual attributes. To this end, we tasked different groups of observers with evaluating similarity among triplets of object concepts along one of those three dimensions. Separate models were derived for the same 190 object concepts represented by 1) images and 2) object labels (i.e., words). Similarity judgements from each task were converted into a representational dissimilarity matrix (RDM) to create six behavioural model RDMs, to be subsequently related to neural RDM series based on EEG data recorded in a different set of participants viewing image versions of same 190 object concepts.

2.2.1 Participants

A total of 695 undergraduate students at the University of Sydney were recruited to take part in the online behavioural study in exchange for course credit. Each participant took part in only one of the six behavioural tasks, and each task had a different number of participants: Perceptual-image task (n=128), Conceptual-image task (n=101), Contextual-image task (n=116), Perceptual-word task (n=113), Conceptual-word task (n=119) and Contextual-word task (n=118). All participants were aged over 18 years; no further demographic information was collected. All participants provided informed consent prior to commencing the experimental task.

2.2.2 Behavioural Task Paradigm

We collected behavioural similarity judgements for our 190 object concepts using an adapted version of the "triplet odd-one-out task" from Hebart et al. (2020), in which observers evaluate the similarity across three object concepts on each trial. In Hebart et al.'s original version of this task, observers saw three object images per trial, and simply selected the object they intuitively felt is the 'odd-one-out', which

implies that the other two objects were more similar. In our adapted version of this task, we instructed online observers to consider triplets of object concepts with respect to either their *Perceptual*, *Conceptual,* or *Contextual* features, selecting the two objects that were most similar along the specified dimension. The task instructions were worded differently depending on the type of similarity judgement required for each task (see Figure 1B). In the *Perceptual* condition, the instructions were: *"Select the two items that are most similar in appearance to each other. It may be helpful to think about: What size is this item? What colour is this item? What shape is this item?".* In the *Conceptual* condition, the prompt was: "*Select the two items that are most conceptually similar to each other. It may be helpful to think about: What is this item used for? How would I interact with this item? What functions does this item have in the real world?*". In the *Contextual* condition, participants were shown: "*Select the two items most likely to be found together in the real world. It may be helpful to think about: Where would I normally find this item?*". These instructions were designed to constrain observers' similarity judgements to the specific dimension of interest, with the understanding that the same trio of objects could be evaluated differently depending on the dimension under consideration (e.g., a spanner and a fork are similar in terms of both their perceptual AND conceptual attributes, but less so in their contextual associations). To reinforce the instructions, participants did 5 practice trials before commencing the experiment proper. These were individually tailored to each version of the task, and included explicit feedback about the selected pair of objects. For example, selecting *ELEPHANT* and *BEAR* on a perceptual similarity practice trial resulted in the feedback text "That was an easy one! An elephant and a bear both have four legs, a tail, eyes, etc.". Conversely, selecting

ELEPHANT and *BAMBOO* resulted in “Hmm I’m not so sure about that one. They don’t really share many visual features”.

Participants were assigned to either a *word* or *image* format of the task (see Figure 2A), and were assigned to only *one* of the three dimensions to judge object similarity. Thus, there were six different triplet similarity tasks with unique participant samples (Perceptual-word, Conceptual-word, Contextual-word, Perceptual-image, Conceptual-image, and Contextual-image). In the word task, three words were randomly drawn from the bank of 190 labels that corresponded to the names of 190 object concepts (i.e., three distinct object concept labels per trial). In the image task, we selected three different object concepts at random, and presented the first exemplar image for each after shuffling the set of 10 exemplars. Participants in the word version of the task completed 250 trials; participants in the image task completed 170 trials. This difference was due to a practical constraint, since images took longer to load in the online study. Alongside the experimental trials, each triplet similarity task also included 5 attention-check trials, designed to probe whether the participants were correctly attending to the instructed dimension. These trials were tailored for each version of the behavioural experiment, such that each trial had an obvious answer with respect to the instructed object dimension (e.g., a perceptual similarity attention-check trial would contain *MOTH, DRAGONFLY*, and *DIRTBIKE*). The total testing time in both versions was approximately 30 minutes.

Note that for all six triplet similarity tasks, each participant was tested with only a subset of the possible triplet combinations from the 190 objects, as testing all 112,835 possible combinations per participant was practically unfeasible. The large number of possible combinations also meant that, even across all participants, we were unable to obtain results from all triplet combinations. However, previous studies

have shown that testing a subset of triplet combinations still provides sufficient coverage to infer most of the pairwise dissimilarities between objects, which is necessary for constructing the model RDM (e.g., Hebart et al., 2020; Moerel, Psihoyos, & Carlson, 2024). The number of trials collected from each task were as follows: Perceptual-image task = 21,760, Conceptual-image task = 17,170, Contextual-image task = 19,720, Perceptual-word task = 28,250, Conceptual-word task = 29,750 and Contextual-word task = 29,500. Although these represented only a fraction of the total possible trials, each trial provides dissimilarity information about three objects (i.e., A-B, A-C, and B-C), allowing for three pairwise comparisons within a single trial. Thus, a relatively small amount of trials was still able to cover a large number of unique object pairs. All behavioural data and relevant analysis code can be accessed at: https://osf.io/jy284/.

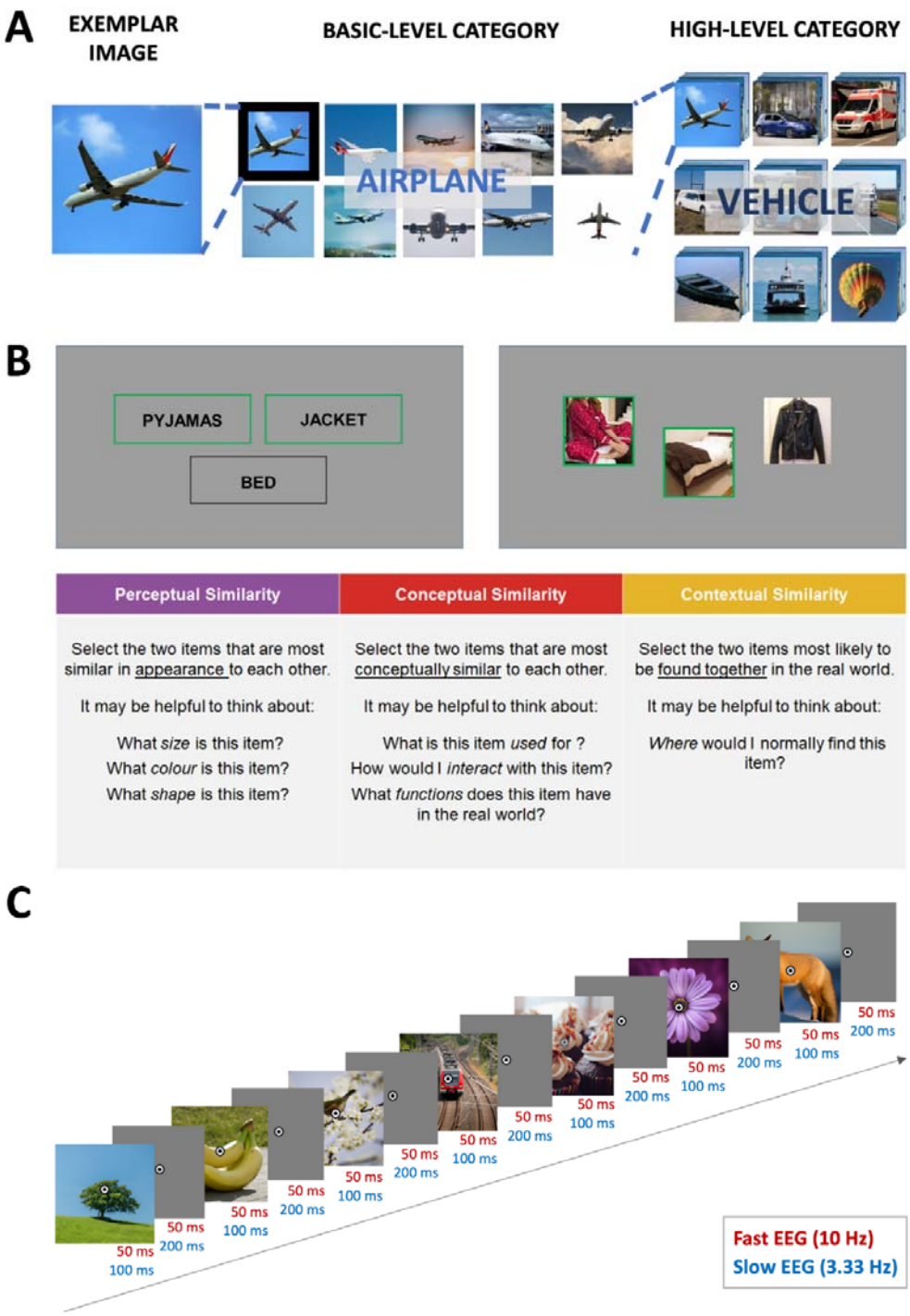

Figure 1. A. Stimuli were 190 object concepts from the THINGS database (Hebart et al., 2019). Each was represented by 10 exemplar images; there were 7-8 object concepts from each of the top 25 high-level categories identified in the original Hebart paper (2019). **B.** Overview of the triplet similarity behavioural task(s). Each

participant was assigned to either a WORD or IMAGE version of the task, and instructed to evaluate triplets of object concepts along one of three objects dimension (fixed across the experiment). Thus, the participant samples for each combination of Stimulus Type and Similarity Type were non-overlapping. **C.** An example of the Rapid Serial Visual Presentation (RSVP) paradigm used in the two EEG experiments that differed in their image presentation rate (i.e., 3.33 Hz vs. 10 Hz). All images in this figure have been replaced with visually similar images from the public domain.

2.3 EEG Data Collection

The current study employed two EEG datasets recorded in response to the same set of 1900 object images, covering 190 concepts. Fast EEG was a pre-existing, publicly available dataset from Grootswagers et al. (2022), comprising 64 channel EEG recordings obtained in 50 observers as they viewed a rapid stream of object images presented at a rate of 10 Hz (image duration = 50 ms; ISI = 50 ms; 1 repetition per image), see Figure 1C. Slow EEG was a novel dataset collected for this study, comprising 128 channel EEG recordings obtained in 20 observers as they viewed object images appearing at a rate of 3.33 Hz (image duration = 100 ms; ISI = 200 ms; 3 repetitions per image), see Figure 1C. Acquisition details for the Fast EEG dataset are provided in Grootswagers et al. (2022); the following section provides details for acquisition of the Slow EEG dataset. For an example Slow EEG dataset, please access: https://osf.io/jy284/.

2.3.1 Participants

Twenty undergraduate students (15 females and one non-binary individual) from the University of Sydney participated in the Slow EEG experiment in exchange for course credit (mean age = 21.85 years, SD = 4.55, age range = 18-34). All participants reported normal or corrected-to-normal vision and normal colour vision, and had no history of psychological or neurological disorders. All but one reported being right-handed. Verbal and written informed consent was obtained from all participants before the experiment, and the study was approved by the Human Ethics Committee of the University of Sydney (ethics ID 2019/340). One participant was excluded from the results due to a technical error in the EEG data, resulting in a final sample of 19 participants.

2.3.2 Experimental Design and Procedure

The Slow EEG paradigm was modelled on the one employed by Grootswagers et al. (2022) to collect the Fast EEG dataset. Where their paper presented multiple exemplars of all 1,854 object concepts from the THINGS dataset (Hebart et al., 2019), here participants viewed a rapid stream of object images representing our selected subset of 190 concepts used in the behavioural experiment. We modified the image presentation rate (3.33 Hz, 100ms image duration, see Figure 1C) used by Grootswagers et al. (2022), on the rationale that a slower presentation rate might enable better capture of not only visual and perceptual processing of objects but also activation of more abstract and semantic information (Carlson et al., 2013; Contini et al., 2017). We selected the first 10 unique images for each per concept, and each of the 1900 object images appeared three times of the course of the full experiment.

Participants sat in a dimly lit room at a distance of ~60 cm before a 1920 x 1080 pixel computer monitor. After being set up for EEG recording, they rested their

hands on a button box and were instructed to maintain their gaze on a small, centrally-displayed black and white bullseye while images were flashing in the background. Participants were instructed to remain still and minimise eye and head movements during the stimulus presentation. Stimuli were presented on a uniform background using the PsychoPy toolbox in Python (Peirce et al., 2019), and were 256 by 265 pixels (approximately 6.25 by 6.25 degrees of visual angle) in size. The task of the participants was to press the button whenever the bullseye turned red (colour changes lasted 100 ms and occurred at random intervals 2-4 times per block). The purpose of this task was to increase attention and engagement. Before the start of the experiment, a practice trial was conducted to ensure that participants understood the task requirements.

All 190 object concepts were presented in a randomised order within each individual sequence; at a rate of 3.33 Hz, this meant that a single sequence lasted 57 seconds. There were 10 exemplar images for each object concept, with each exemplar presented three times across the entire experiment (i.e., 30 sequences in total). This resulted in a total of 5,700 stimulus presentations per participant (190 concepts x 10 exemplars x 3 repetitions). Participants were encouraged to take sufficient breaks between sequences to mitigate screen fatigue. The progress of the experiment was indicated on the screen between sequences by displaying the number of the upcoming sequence (*e.g.,* "2/30", "18/30"). The entire experiment, including breaks, took approximately 35 minutes.

2.3.3 EEG Recording and Preprocessing

During the stimulus presentation, participants' brain activity was continuously recorded using a BrainVision ActiChamp system at a sampling rate of 1000 Hz. The standard 128-channel EEG cap (Brain Products; GmbH, Herrsching, Germany) was

fitted to the participants, corresponding to the 10-20 international system of electrode locations (Oostenveld & Praamstra, 2001). We applied electrolyte gel to keep the impedances below 10 kΩ, and the electrodes were referenced to FCz.

The offline preprocessing of EEG data was performed using the EEGLAB toolbox in MATLAB (Delorme & Makeig, 2004). A Hamming windowed FIR filter was applied with a low-pass filter of 100 Hz and a high-pass filter of 0.1 Hz. The data were then re-referenced to the average reference and downsampled to a rate of 250 Hz. Epochs were created for each stimulus presentation from -100 ms to 800 ms relative to the stimulus onset. No further preprocessing steps were taken.

2.4 Representational Similarity Analysis

To assess whether the behavioural data of object similarity judgements could explain the dynamics of neural representational structure over time, we used Representational Similarity Analysis (RSA; Kriegeskorte, Mur, & Bandettini, 2008). We created Representational Dissimilarity Matrices (RDMs), which capture the dissimilarity between pairs of experimental stimuli based on their representational patterns. For the behavioural data, RDMs were generated from participants' similarity judgments of objects, with one RDM created for each of six triplet similarity tasks. As for the neural data, RDMs reflected the similarity or dissimilarity in the neural activation patterns evoked by each pair of the 190 concepts.

2.4.1 Behavioural model RDMs

Before creating the behavioural model RDMs, we firstly removed any participants who made an incorrect selection on more than 3 of the 5 attention-check trials, on the rationale that they were not correctly attending to the instructed object dimension. This resulted in the following final participant samples: Perceptual-image

task (n = 114), Conceptual-image task (n = 100), Contextual-image task (n = 108), Perceptual-word task (n = 98), Conceptual-word task (n = 105) and Contextual-word task (n = 103). Following this, we constructed 6 RDMs based on the six different triplet tasks. These RDMs were constructed at the level of object concepts, with cells reflecting the pairwise dissimilarity between objects' selection rates (ranging between 0 and 1). This value was computed from the triplet similarity task data, by calculating the proportion in which two objects were chosen together out of all the instances when they were shown together in a triplet. A value of 1 indicated extreme dissimilarity, meaning that the two objects were never chosen together, while a value of 0 indicated extreme similarity, meaning the objects were always chosen together. As outlined above, because we presented only a subset of the total possible triplet combinations in our behavioural tasks, some cells of these RDMs had no dissimilarity score, indicating that the respective object pairs were never shown together in a triplet. The proportion of missing dissimilarity values in the six behavioural model RDMs were as follows: Perceptual-word = 1.65%, Conceptual-word = 0.52%, Contextual-word = 0.60%, Perceptual-image = 1.69%, Conceptual-image = 7.89%, and Contextual-image = 6.22%.

We inspected the validity of our behaviourally-derived models by correlating them with binary models representing ground truth object properties. These included models of high-level category, naturalness, animacy, outdoor/indoor association and real-world size (smaller or larger than a shoebox). Each object pair was given a binary value of either 0 or 1, indicating identicality or difference in the given object property (Figure 2B). As is clear in Figure 2C, there were significant correlations among most of our models, with the strongest correlations emerging between the Conceptual-word and Naturalness models (r = .53, p<.00001), and the Conceptual-

image and Naturalness models (r = .48, p < .00001). Notably, strong correlations were evident between the image and word versions of each similarity judgement task, reflected in the clustering of these models when visualised using 2D multidimensional scaling (Figure 2D).

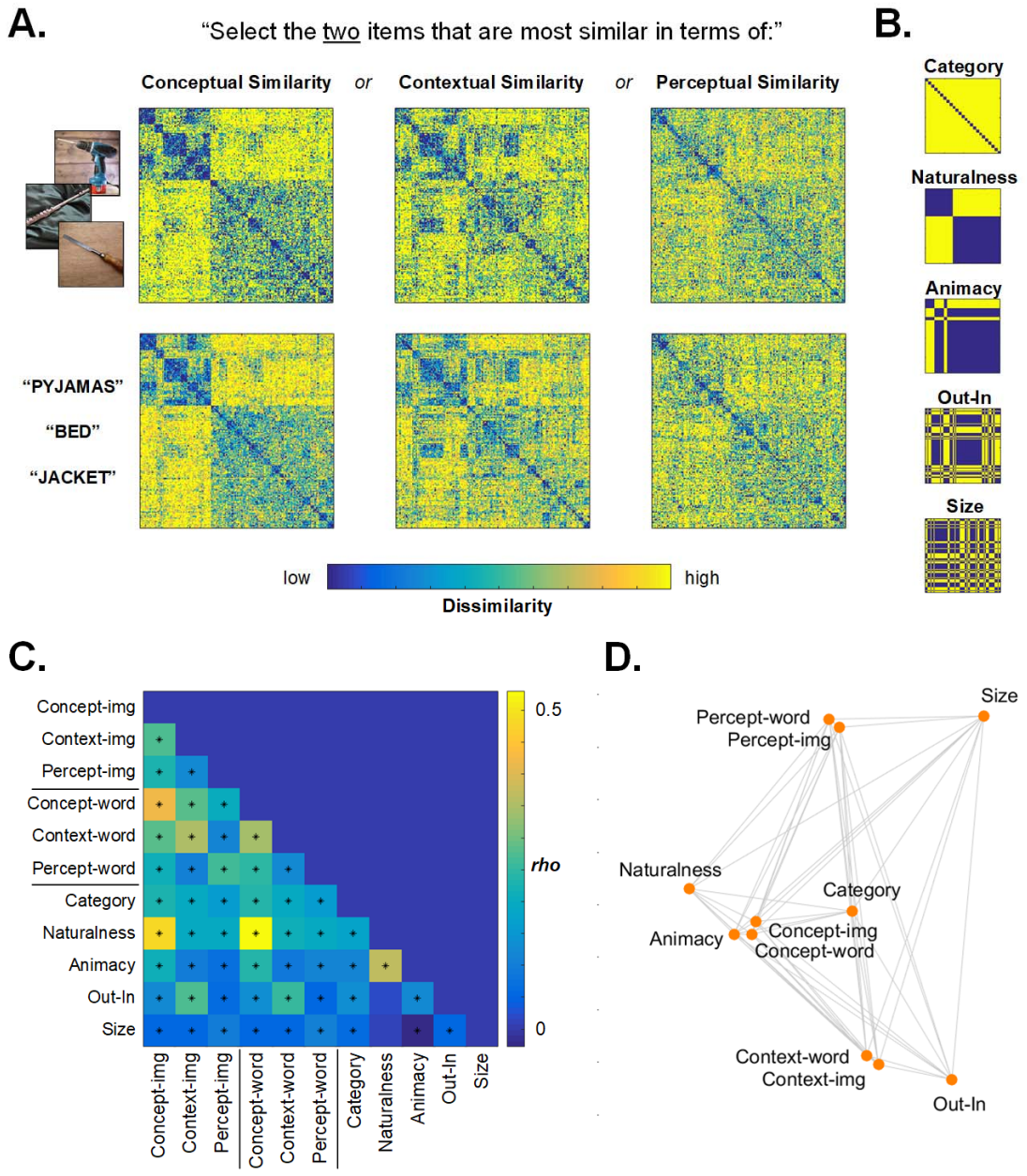

Figure 2. A) Behavioural RDMs derived from each of the 6 behavioural triplet similarity tasks. Non-overlapping groups of online observers saw either triplets of object-images or object-names and had to select the pair with the highest conceptual similarity, contextual similarity, or perceptual similarity. B) Binary models for the 190 object concepts. C) Intercorrelation matrix for the six behavioural RDMs and the binary models. Stars indicate correlations significant at $p < .001$, FDR corrected. D) Model similarity reflected in 2D multidimensional scaling. Note the close proximity of word/image versions for each object similarity dimension.

2.4.2 Slow EEG RDMs

We subjected the preprocessed EEG data from the Slow EEG task to RSA to produce an RDM series reflecting time-resolved pairwise dissimilarity between all 190 object-concepts. Decoding accuracy served to index the degree of dissimilarity between object concepts' neural activation patterns, with higher decoding accuracy taken to reflect more dissociable object representations. In line with previous studies (e.g., Grootswagers, Wardle, & Carlson, 2017), we ran the decoding analysis on preprocessed EEG data collected from all 128 channel voltages, using the CoSMoMVPA MATLAB toolbox (Oosterhof, Connolly, & Haxby, 2016). A linear discriminant analysis (LDA) classifier was used to identify the decision boundary that could best differentiate the brain activation patterns evoked by objects. We implemented a leave-one-sequence-out cross-validation procedure, wherein the classifier was trained iteratively on all sequences of EEG data except one, which was kept aside to serve as the test data. We repeated this process for all sequences to ensure that every sequence was used for testing. During training, the classifier was tasked with distinguishing the neural activity patterns evoked by pairs of object

objects and classifying them into two categories. This process was performed for every possible pairwise combination of the 190 object concepts shown in that sequence. The classifier underwent training and testing at each timepoint in the epoch between -100 and 800 ms. This process was repeated for each participant, resulting in one time-varying neural RDM per participant for each time-point.

2.4.3 Fast EEG RDMs

To create corresponding RDMs based on the Fast EEG dataset, we applied the same pre-processing and analysis steps described for the Slow EEG to the raw data from Grootswagers et al. (2022). This EEG dataset consisted of EEG recordings from 50 participants presented with 1,854 THINGS concepts. Four participants were excluded from the analysis due to poor signal quality or equipment failure, resulting in data from 46 participants. From this original dataset, we extracted the data pertaining to the first 10 images of the 190 object concepts, aligning with the concepts and stimuli used in our behavioural study and the collection of new EEG data (Slow EEG). We matched the epochs in Slow EEG that were created between -100 ms to 800 ms relative to stimulus onset (225 time-points). We then used pairwise decoding with a leave-one-sequence-out cross-validation procedure to obtain an RDM for each participant and timepoint in the epoch.

2.4.5 Correlation between Behavioural Model RDMs and EEG Neural RDMs

To examine the degree to which our behaviourally-derived RDMs could account for unique variance in the neural response to the same object concepts, we aimed to correlate each of the six behavioural RDMs with the two time-varying neural RDMs. Specifically, we used partial correlations to examine each model's independent

capacity to explain the neural representational structure. For this analysis we grouped the behavioural models by modality: (1) *image* models, that captured the three similarity dimensions from the image-based tasks (i.e., Perceptual-image, Conceptual-image, Contextual-image), and (2) *word* models, which represented the three similarity dimensions derived from the word-based tasks (i.e., Perceptual-word, Conceptual-word, Contextual-word). Thus, four sets of partial correlation analyses were conducted: (1) Fast EEG RDM with three image model RDMs, (2) Fast EEG RDM with three word model RDMs, (3) Slow EEG RDM with three image model RDMS, and (4) Slow EEG RDM with three word model RDMs. Within each analysis, Spearman's rank correlation coefficients were calculated between the neural RDM and a model RDM, while partialling out the variance explained by the other two model RDMs within the same task modality. For example, the partial correlation of the Perceptual-image model was calculated by partialling out the Conceptual-image and Contextual-image models. The partial correlations were computed across all time points in the neural RDM. Due to the lack of behavioural data for one object ('spatula'), we excluded it and only correlated 189 objects in both the neural and model RDMs. Additionally, as some cells in the model RDMs did not have dissimilarity scores, we used a geometric reconstruction method to complete these missing dissimilarity scores (Moerel & Grootswagers, 2025) before using them in the correlation analysis.

Finally, we calculated difference scores between the partial correlation values associated with each model using a simple arithmetic subtraction. For example, difference scores were calculated between the partial correlations of the perceptual and conceptual models within the same task (i.e., Perceptual-image minus Conceptual-image; Perceptual-word minus Conceptual-word), and between image

and word modalities within the same similarity dimension (i.e., Perceptual-image minus Perceptual-word; Conceptual-image minus Conceptual-word).

2.5 Statistical Inference

We evaluated evidence for positive correlations between the behavioural models and the two EEG dataset using Bayesian hypothesis testing that considered evidence supporting the alternative hypothesis (i.e., H_a) over the null hypothesis (i.e., H_0). In this context, we report Bayes factors (BFs) which assess the likelihood of a partial correlation (H_a) as compared to no partial correlation (H_0), given the set of obtained correlation values across participants at each time point. Specifically, we defined H_a as the existence of a positive partial correlation between the neural and model RDMs (i.e., as the dissimilarity between two stimuli increases in the neural RDM, the dissimilarity in the behavioural model RDM also tends to increase), while H_0 posited that the partial correlation between neural and model RDMs was zero (i.e., no relationship between the dissimilarity of two stimuli in the neural RDM and the model RDM). In general, a BF greater than 1 indicates evidence in favour of H_a, while a BF less than 1 suggests evidence in favour of H_0. We interpreted BF thresholds as follows: BF > 10 was considered strong evidence, and BF > 3 was considered weak evidence in favour of H_a. Conversely, BF < 1/10 indicated strong evidence, and BF < 1/3 indicated weak evidence in favour of H_0. When 1/3 < BF < 3, this was interpreted as insufficient evidence for either hypothesis. We used a threshold of BF > 3 to calculate the onset time of above chance correlations. We required at least two consecutive BFs > 3 for the onset, an isolated BF at a single time point, meeting the threshold of 3 or 1/3 but without consecutive BFs reaching these thresholds, was treated as inconclusive evidence for either hypothesis.

BFs were calculated using the Bayes Factor package in R (Richard D Morey, Rouder, Jamil, & Morey, 2015). The null hypothesis was defined using a point null (R. D. Morey & Rouder, 2011) and we applied a half-Cauchy prior for the alternative hypothesis to conduct a directional test to test for positive partial correlations. The prior range for the alternative hypothesis was defined from d = 0.5 to d = ∞ to exclude small effects between the interval of d = 0 and d = 0.5, as these have been shown to occur at chance under the null hypothesis (Teichmann, Moerel, Baker, & Grootswagers, 2022). The prior width was set to a medium (r = 0.707), which is the default setting in the BayesFactor R package.

3. RESULTS

We first examined whether brain activity during passive viewing of rapid object image streams could be explained by behavioral models reflecting perceptual, conceptual, and contextual object similarities. The six models were grouped by modality: three based on image-based tasks and three on word-based tasks. For each modality, we computed partial correlations between each model and time-resolved EEG data, controlling for the other two models within the same group. This approach allowed us to identify models that uniquely explained variance in the EEG signal beyond what was captured by the other models of the same modality.

3.1 Correlations between behavioural models and Fast EEG

Figure 3 shows the partial correlations between the Fast EEG dataset and the three object property models derived from the image-based triplet similarity task (Figure 3A) and the word-based triplet similarity task (Figure 3B). We observed partial correlation between the Fast EEG dataset and the Perceptual-image model beginning 108 ms after stimulus onset and peaking at 192 ms. There was also a

comparatively later partial correlation with the Conceptual-image model beginning from 184 ms, which coincides with its peak at 188 ms. There was evidence for no positive partial correlation with the Contextual-image model.

For the word-based object similarity models, we found evidence for a partial correlation with the Perceptual-word model and Fast EEG dataset starting from 124 ms, which coincides with its peak. The Conceptual-word model also correlated with Fast EEG from 176 ms, with a distinct single peak occurring at 196 ms. From this, we inferred that the Conceptual-word model had a later correlation onset and peak compared to the Perceptual-word model, mirroring the pattern observed in the image models. Furthermore, compared to the image models, the word models generally had a later onset and peak of partial correlation (see Table 1 for correlation onsets and peaks for each model). Finally, there was either insufficient evidence or evidence of no partial correlation between the Contextual-word model and the Fast EEG dataset.

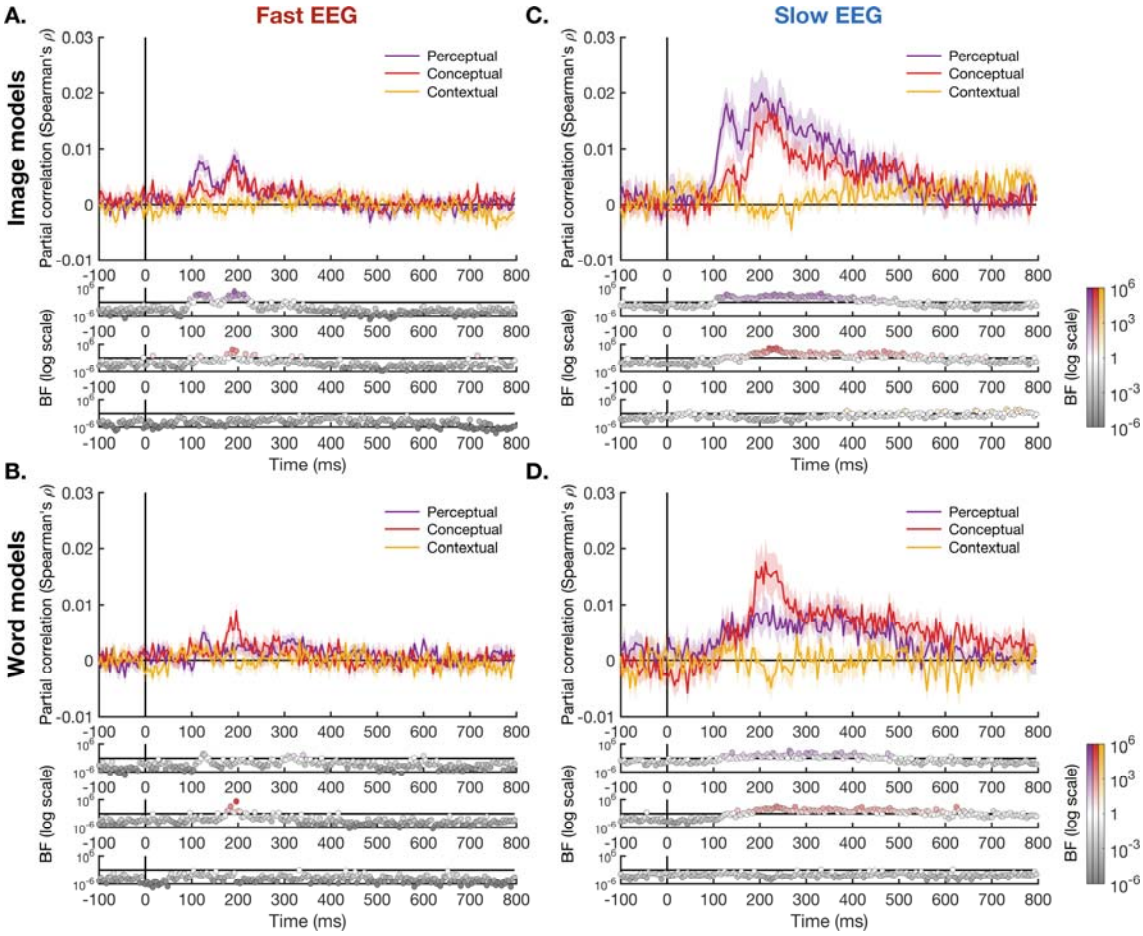

Figure 3. Partial Correlations Between Behavioural Models and two EEG Datasets. Partial correlations (Spearman's ρ) were calculated between the EEG neural RDMs from two datasets (reflected in columns) and the six behavioural model RDMs grouped by modality (reflected in rows). Partial correlations were computed at each time point from stimulus onset by removing the variance explained by the other two models within the same modality from each model's full correlation. Shaded areas represent standard errors. Time (ms) is relative to the stimulus onset at 0 ms. The logarithmic scale of Bayes factors (BFs) below each plot indicates the strength of evidence for two opposing hypotheses at each individual timepoint. BF>1 were represented by circles filled with the corresponding plot colour and denote evidence

for alternative hypothesis (i.e., positive or negative correlation), BF≈1 were represented by white circles, which indicate insufficient evidence for either hypotheses, and BF<1 were represented by grey circles and indicate evidence for null hypothesis (i.e., zero-correlation).

3.2 Correlations between behavioural models and Slow EEG

The right column of Figure 3 shows the partial correlations between the Slow EEG dataset and the behavioural models derived from the image-based triplet similarity task (Figure 3C) and the word-based triplet similarity task (Figure 3D). For the image-based models, we found evidence of a partial correlation between Slow EEG and the Perceptual-image mode beginning 108 ms after stimulus onset and peaking at 204 ms. The Conceptual-image model displayed a correlation onset of 160 ms, reaching its peak at 220 ms. Notably, we also found evidence of a partial correlation between the Contextual-image model and EEG, starting from 384 ms and peaking at 732 ms. These results show that the correlation onset of the Conceptual-image model occurred relatively later compared to the Perceptual-image model, but the peak correlation occurred around a similar time for both models. Additionally, the Contextual-image model correlated with EEG much later in the time course compared to the other two image models.

Figure 3D shows the partial correlations between Slow EEG and the three word models. The Perceptual-word model's partial correlation started from 120 ms and peaked at 368 ms, while the Conceptual-word model correlated with EEG from 176 ms with a single distinct peak at 212 ms. For the Contextual-word model, we

found either evidence for no correlation, or else insufficient evidence to support either outcome.

Fast EEG						Slow EEG					
Image-task			Word-task			Image-task			Word-task		
Per-cept	**Con-cept**	**Con-text**	**Per-cept**	**Con-cept**	**Con-text**	**Per-cept**	**Con-cept**	**Con-text**	**Per-cept**	**Con-cept**	**Con-text**
108 ms	184 ms	N.E.	124 ms	176 ms	N.E.	108 ms	160 ms	384 ms	120 ms	176 ms	N.E.
192 ms	188 ms	N.E.	124 ms	196 ms	N.E.	204 ms	220 ms	732 ms	368 ms	212 ms	N.E.

Table 1. Partial Correlation Onsets and Peaks. The time points (ms) corresponding to correlation onsets (top row) and peaks (bottom row) were identified using Bayes Factors (BFs) cut-offs. N.E. denotes no evidence.

3.3. Summary of EEG Datasets

In summary, the object property models that uniquely explained the dynamic neural representation of the stimuli were largely consistent across both EEG datasets. Specifically, the perceptual and conceptual models, whether derived from the image or word-task, consistently accounted for the neural response to object images in both Fast and Slow EEG. However, for the contextual models, we found evidence only for the Contextual-image model correlating with Slow EEG, which had limited explanatory power due to the correlation onset and peak occurring at late time

points (384 ms and 732 ms respectively). All other statistical analyses provided insufficient evidence or evidence of no partial correlation between the contextual models and EEG.

From these results, we concluded that Slow EEG appeared to be a ‘scaled-up’ version of Fast EEG, with similar timings of correlation onsets and peak time points in the perceptual and conceptual models. This is likely due to the threefold increase in image presentations in Slow EEG contributing to a higher signal-to-noise ratio compared to Fast EEG. Given the high consistency of findings across the EEG datasets, and considering the enhanced power provided by Slow EEG due to its improved experimental design, our subsequent analyses focused exclusively on Slow EEG. Within this dataset, we asked more focused questions, focussing on the difference between the perceptual and conceptual models in explaining neural data, whether the two conceptual models were of the same nature, and whether the contextual models played any role in explaining neural data.

3.4 Comparison of Perceptual and Conceptual models in explaining neural responses

In Figure 4A, we examined the relative contributions of the perceptual and conceptual models on explaining the neural representational structure of Slow EEG by subtracting the partial correlation of the conceptual model from the perceptual model, separately for each task modality. A two-tailed Bayesian *t*-test was used to compare the resulting difference profile to zero.

When we compared the Perceptual-image model with the Conceptual-image model, their difference score exceeded zero during an early time window (108-140 ms), indicating that the Perceptual-image model provided a better explanation of the

neural response to object images than the Conceptual-image model during this early phase. Outside this window, there was either no evidence or insufficient evidence of a difference between the two models, suggesting that both models performed equally well at explaining EEG during this period.

Comparing the performance of the Perceptual-word with the Conceptual-word model, only a few isolated time points showed evidence of a difference. Since no two or more consecutive time points showed such evidence, we concluded that there was limited evidence of difference between the Perceptual-word and Conceptual-word models, indicating that both models provided comparably good explanations of the EEG data across all time points.

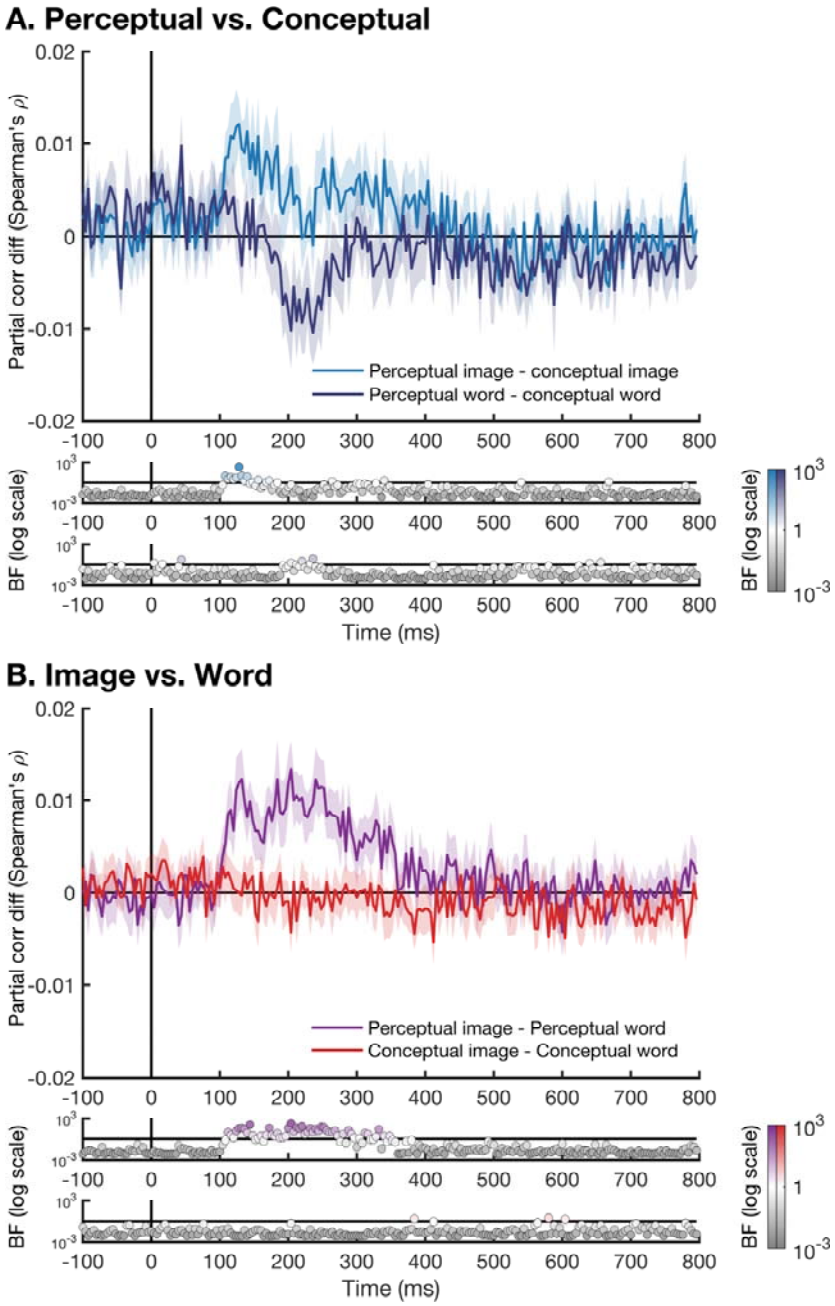

Figure 4. Spearman's *ρ* differences contrasting the predictive power for various behavioural models. (A) Perceptual - Conceptual partial correlation differences calculated for each modality (i.e., Image or Word) separately. **(B)** Image – Word partial correlation differences calculated for each similarity dimension (i.e., Perceptual or Conceptual) separately. Shaded areas indicate standard error. Lower panels are log-scaled Bayes Factors testing difference scores ≠ 0.

In Figure 4B, we compared the modality in which the triplet similarity task was presented (i.e., image vs. word) within the same object property (i.e., perceptual or conceptual). When comparing the two perceptual models, we observed that the Perceptual-image model had a greater unique explanation of EEG neural response compared to the Perceptual-word model, during the period of 112 to 332 ms, although included a few time points that showed insufficient evidence. In contrast, there was no sustained evidence of a difference between the Conceptual-image and Conceptual-word models. Our analysis of the difference between the model performances against Slow EEG suggests that: (1) the Perceptual-image model outperformed the Conceptual-image model at early time points; (2) the Perceptual-image model was better predictor of the (image-derived) EEG responses compared to the Perceptual-word model across a broad time window; (3) there was limited evidence of a difference in explanatory power between the Perceptual-word and Conceptual-word models, as well as the Conceptual-image and Conceptual-word models.

3.3 Do Conceptual image and word models capture the same neural structure?

Given that the conceptual models explained the EEG data equally well regardless of whether they were derived from similarity judgements of images or words, we next asked whether the two models captured the *same* conceptual information about objects. To investigate this, we examined the partial correlations for the Conceptual-image and Conceptual-word models, when partialling out the other model. This allowed us to assess the unique explanatory power of one model for our EEG data, over and above the other model. We also computed their full correlations with the EEG data to as a baseline. The results are plotted in Figure 5. Interestingly,

although each model's partial correlations did appear reduced relative to their full correlations, removing the shared variance between the Conceptual-image and Conceptual-word model did not fully eliminate either model's unique explanatory power. This suggests that the two conceptual models each had unique contributions for explaining the neural responses to objects, potentially capturing different aspects of conceptual object knowledge. This possibility would seem further underscored by the fact that although the Conceptual-image and Conceptual-word model were significantly correlated, they were by no means identical (see Figure 2).

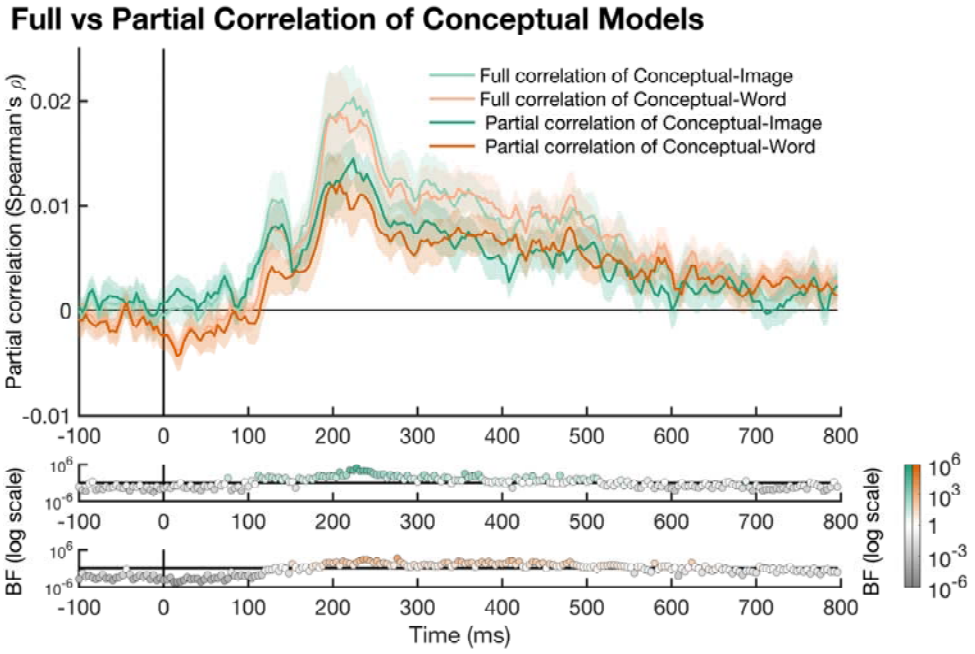

Figure 5. Full and Partial Correlations of Conceptual-image and Conceptual-word models. The pale lines represent full correlations between each conceptual model and Slow EEG. The solid lines represent partial correlations of each conceptual model using the other conceptual model as its covariate. The lines were temporally smoothed with a kernel of 3 samples (12 ms) for visibility. The Bayes

factors (BFs) were based on unsmoothed data and were plotted only for the partial correlations.

3.4 Do Contextual models play any role in explaining the neural response to objects?

Our final analysis focused specifically on the contextual object property models. Our previous analysis showed only the Contextual-image model demonstrated partial correlations with Slow EEG at isolated late time points (see Figure 3C and Table 1). However, it remains unclear whether behaviourally derived models of objects' contextual associations lack explanatory power altogether, or if their explanatory power is simply not unique, due to shared variance with the perceptual and/or conceptual models. To examine this, we calculated the partial correlations between each contextual model and Slow EEG while partialling out the other model. As a baseline, we also calculated the full correlation between each contextual model and Slow EEG (i.e., without removing shared variance with any other model). In doing so, we aimed to determine whether the contextual model in isolation could account for any variance in the EEG data, and if so, clarify the extent to which this variance overlaps with that explained by the perceptual and/or conceptual models.

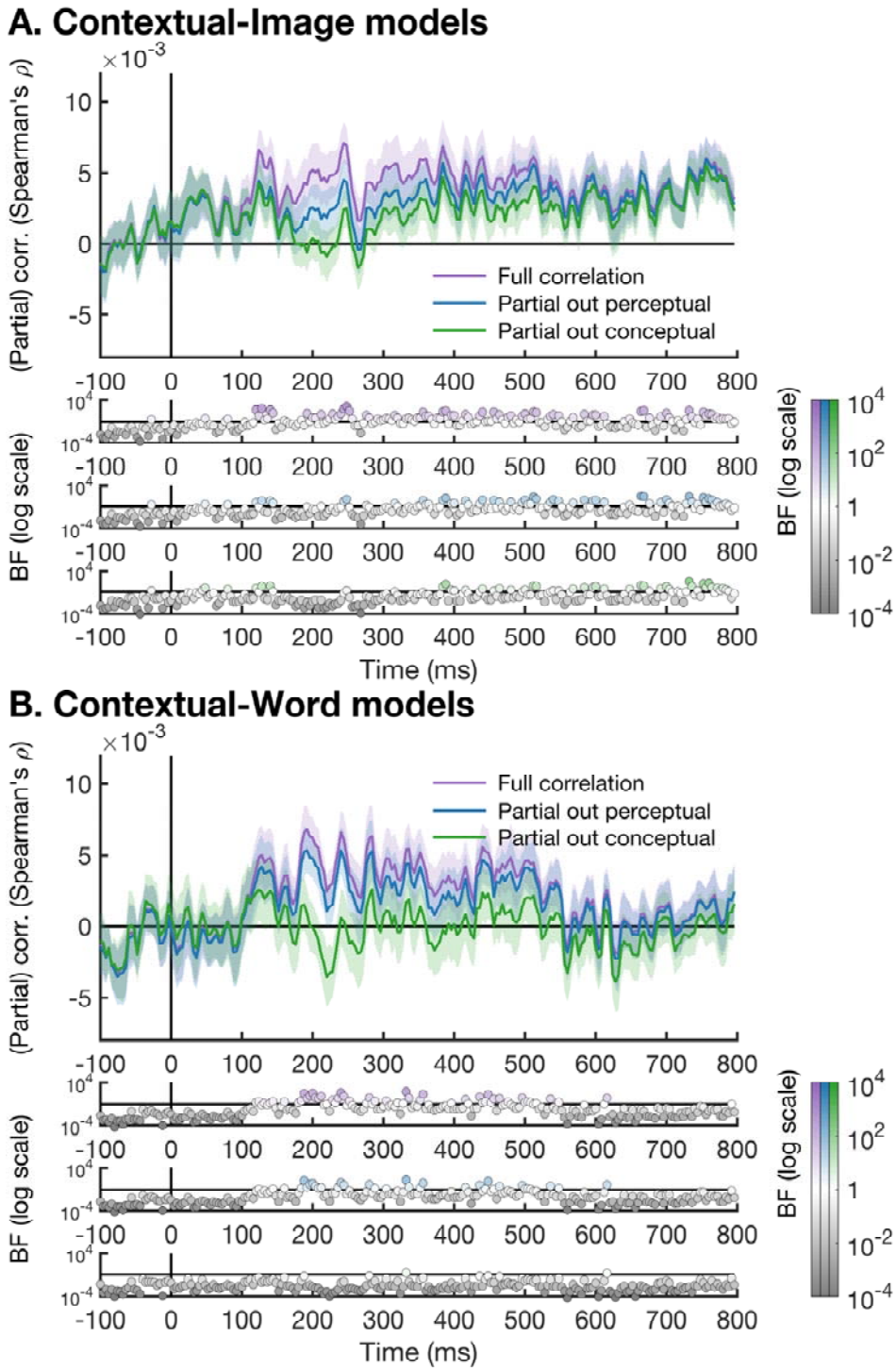

Figure 6. Full and Partial Correlations for the Contextual Models based on **(A)** Image-task and **(B)** Word task. The lines were temporally smoothed with a kernel of 3 samples (12 ms) for visibility. Below each plot, Bayes factors (BFs) appear for the full correlation (top), partial correlation controlling for the perceptual model within the

same modality (middle) and partial correlation controlling for the conceptual model within the same modality (bottom). The Bayes factors (BFs) were based on unsmoothed data.

Figure 6A shows the full and partial correlations of the Contextual-image model with EEG. We found evidence that the Contextual-image model did correlate with the EEG data when no other models were taken into account (onset at 120 ms and peaking at 244 ms). When the variance explained by the Perceptual-image model was partialled out, we retained evidence of a partial correlation between the Contextual-image model and EEG from 140 ms onwards. When the covariate was changed to be the Conceptual-image model, we retained evidence of a partial correlation between the Contextual-image model and EEG during the late time window from 384 ms. This would suggest that the Conceptual-image model shared a similar amount of variance with the Contextual-image model, and that when variance accounted for by each were taken into consideration, the Contextual-image model retained little unique explanatory power.

Figure 6B shows the full and partial correlations of the Contextual-word model with EEG. Evidence indicated that the Contextual-word model began correlating with EEG at 184 ms. When the Perceptual-word model was included as a covariate and partialled out from the full correlation, the correlations were mostly preserved, with a shifted onset of 196 ms. This suggested minimal shared variance between the contextual and the Perceptual-word models. However, when the covariate was switched to the Conceptual-word model, there was no longer any evidence supporting the Contextual-word model's unique explanatory power, in contrast to the results when the Perceptual-word model was partialled out.

In general, these findings suggest that the contextual models shared relatively more variance with the conceptual models than the perceptual models, particularly in the case of word-based models. While the contextual models do explain variance in the EEG data, they do not provide unique explanatory power beyond what is captured by the conceptual models.

4. DISCUSSION

This study investigated how contextual, perceptual, and conceptual object attributes contribute to the neural responses evoked by visual objects. We used representational similarity analysis (RSA) to correlate two EEG datasets recorded during the passive viewing of object images with behavioural models based on similarity judgements of objects' perceptual, conceptual, or contextual properties. Separate behavioural models were derived for image and word label versions of the objects. Our findings revealed that behavioural similarity judgements along the perceptual and conceptual dimensions accounted for independent aspects of the neural response to object images. Our results underscore the robustness of object representations in the human brain, as the temporal dynamics of perceptual and conceptual object feature models' explanatory power were consistent across both word-based and image-based models, and across EEG datasets with differing signal-to-noise ratios due to differences in presentation rate, stimulus repetition, and inter-stimulus interval. Notably, there was no evidence that contextual object attributes captured by in our behavioural models were meaningfully related to the neural response elicited by object images over and above what could be explained by the perceptual and conceptual models.

A perceptual to conceptual continuum of object features across both image and word modalities

A key finding from our study is that the perceptual features of objects deemed relevant by human observers dominated the early stages of the neural response to object images, with conceptual aspects of objects better explaining a later stage processing. Information about objects' perceptual attributes emerged as early as approximately 100 ms after stimulus onset, while conceptual information was reflected in the neural response to object images from approximately 160 ms onwards. This pattern was consistent regardless of the image presentation rate, and evident using models derived from both the image and word modalities, although onsets were slightly later for the Perceptual-word compared to image models (see Table 1). These findings largely align with established object recognition literature that has identified early processing of lower level visual features (such as object shape and colour) followed by abstract conceptual attributes (such as object category) (Carlson et al., 2013; Cichy, Pantazis, & Oliva, 2014; Contini, Goddard, Grootswagers, Williams, & Carlson, 2020; Contini et al., 2017; Grootswagers, Robinson, & Carlson, 2019; Grootswagers, Robinson, Shatek, et al., 2019; Teichmann et al., 2025).

We found that perceptual similarity bewteen object images uniquely explained EEG neural response from approximately 100 ms after stimulus onset, peaking at approximately 200 ms for both Fast and Slow EEG. This is in line with previous studies that have compared behavioural models of perceived visual similarity to EEG responses to visual stimuli (Cichy et al., 2019; Wardle et al., 2016). Cichy and colleagues (2019) found the unique emergence of visual features such as colour and shape at 82 ms and 183 ms respectively, peaking at 82-117 ms and 183-202 ms.

Similarly, Wardle et al. found that the perceived similarity of artificial shapes explained neural response from as early as 50 ms, with the highest correlation observed at 150 ms. Although variations in experimental designs and stimuli make direct comparisons of correlation onsets and peaks between studies challenging (Contini et al., 2017), our findings are consistent with the broader agreement that visual features underlying behaviour are processed within the first 200 ms of visual object recognition (Carlson et al., 2013; Cichy et al., 2014; Contini et al., 2017). While we cannot determine which specific visual features participants focused on when evaluating objects' perceptual similarity, the Perceptual-image model demonstrated the earliest time point of unique correlation among all behavioural models, which suggest that participants likely relied on lower-level properties of objects such as colour or shape to guide their similarity judgements. The temporal dynamics associated with conceptual attributes of object images observed here also concord with extant findings. In our case, the Conceptual-image model uniquely explained the EEG response from approximately 160 ms onwards, peaking around 200 ms, a relatively later onset but similar peak compared to the Perceptual-image model. The partly overlapping time points of correlation between the perceptual and conceptual image models highlight the dynamic evolution of representations in the brain, transitioning from lower-level perceptual to higher-level semantic properties over the first 200 ms after stimulus onset (Bankson et al., 2018; Clarke et al., 2013, 2015).

Turning to the word-based models of object dimensions, we found evidence for a unique explanatory role of the Perceptual-word model for EEG datasets from approximately 120 ms after stimulus onset. This suggests that perceptual properties accessible via object labels alone are represented during the early stages of visual object perception. When participants read a word like "AIRPLANE" and are asked to

consider its perceptual properties, it likely would have activated the associated visual features (*e.g.,* shape, colour) in their minds (Pearson, Naselaris, Holmes, & Kosslyn, 2015). Research on mental imagery indicates that imagining a visual stimulus activates the visual cortex, engaging similar neural mechanisms to those involved in perceiving an actual object (Kosslyn, Thompson, Klm, & Alpert, 1995; Mechelli, Price, Friston, & Ishai, 2004; O'Craven & Kanwisher, 2000). The fact that the Perceptual-word model's correlations onset and peak arose later than those for the Perceptual-image model would suggest that the specific perceptual properties tapped by object label similarity judgements are somewhat more abstract than those tapped by image-based judgements. The relatively later onset of the Conceptual-word model's explanation of EEG (approximately 180 ms after stimulus onset) further suggests that the specific abstract/semantic features of objects that observers access via object labels are represented in the neural response to objects somewhat later than their stereotypically-associated visual features. Taken together, these results suggest that reading object-labels can activate both perceptual and conceptual object knowledge, but in a different manner to when observers encounter an object image, extracting visual features from the stimuli and derive their conceptual meaning.

A unique aspect of our study is its direct comparison of behaviourally-derived object property models based on judgements elicited by word and image versions of the same object concepts. Our findings suggest there is significant overlap in the object knowledge accessed via object image and word labels, in that both contribute to explaining the neural activity involved in visual object recognition. However, there appears to be a trend where lexically-accessed visual and conceptual features explain neural processes at later time points compared to image-derived object knowledge for the perceptual models. In demonstrating that lexically-accessed

perceptual and conceptual features can also explain the neural responses to visual objects, we add to an existing literature that has mostly relied on object images to generate behavioural object dimension models (Cichy et al., 2019; Giari et al., 2020). The findings here are some of the first to capture how presentation modality (word vs. image) differentially activates object knowledge within the same dimension, with object labels facilitating access to semantic aspects of object that are less visually confounded than those elicited by object images (Giari et al., 2020). Precedent for our approach does exist in terms of neural responses, with Giari et al. (2020) measuring neural responses for image and word versions of the same objects with EEG. Specifically, they compared conceptual object similarity with the representational structure of MEG responses elicited by both pictures and words, to delineate the time course of higher-level semantic processing evoked by reading object labels (which are not subject to the visual-conceptual covariance present in object images). Several factors distinguish our study from Giari et al. (2020): Where they used a category-typicality rating task during MEG recording to activate conceptual object representations, the neural representations of objects in our data were acquired under passive viewing conditions. That is, we deliberately did not direct attention to object features, but rather engaged participants in an orthogonal fixation colour change detection task that rendered the objects task-irrelevant. That we find evidence of conceptual processing using both an orthogonal task and a faster presentation rate than Giari et al. (100 ms vs. 400 ms) highlights the rapid and automatic nature of object concept activations during visual perception.

Contrasting perceptual and conceptual models within each modality

When comparing the performance of different models based on object dimension or modality against the EEG neural data, we found that the Perceptual-

image model outperformed the Conceptual-image model at early time points (approximately 100-140 ms after stimulus onset). The early dominance of the Perceptual-image model over the Conceptual-image model further supports our findings from the individual partial correlations of the behavioural models across the two modalities and EEG datasets, indicating that perceptual features are processed earlier than conceptual features. There was limited evidence of a difference in explanatory power between the Perceptual-word and Conceptual-word models. However, this still suggests a general pattern of later processing of conceptual features compared to perceptual features, consistent with the Perceptual-image and Conceptual-image models. Taken together, this suggests that for image-derived behavioural models, perceptual features explain EEG data better than conceptual features. The same was not true for the word-based models, where we observed a trend for the Conceptual-word model explaining the neural responses better than the Perceptual-word model, although not reaching the threshold for evidence. Future studies could explore the factors contributing to this modality-specific distinction, particularly in how perceptual and conceptual features are evoked differently by pictorial and lexical stimuli, which could offer more insights into the temporal dynamics of perceptual and conceptual feature integration in the brain.

Contrasting image- and word-based models within each object dimension

The superior fit of the Perceptual-image model compared to the Perceptual-word model across a broad time range of approximately 100-330 ms suggests that perceptual features evoked by directly viewing object images better explain the EEG than those evoked by reading word labels. As discussed earlier, reading word labels requires a degree of mentalisation to evoke perceptual features, which may vary

significantly across participants. The variability likely limits the explanatory power of the Perceptual-word model compared to the Perceptual-image model. In contrast, there was no evidence that the two conceptual models based on different modalities differed in their explanatory power. Moreover, incorporating the Conceptual-word and Conceptual-image models into a single analysis did not reduce either model's partial correlation to zero (Figure 5), suggesting that the two captured somewhat distinct elements of objects' conceptual attributes. This could reflect different ways of accessing conceptual knowledge: image-cued activation may involve processing visual features to retrieve associated conceptual attributes, while word-cued activation relies on lexical processing to access the conceptual knowledge of the object stored in the brain.

Contextual object associations do not uniquely predict neural responses to objects

In contrast to the relatively clear connection between the perceptual and conceptual models and the neural data, we found only fleeting evidence that the models of objects' contextual associations uniquely explained the neural response to object images. This evidence was limited to the Contextual-image model and the Slow EEG dataset, and corresponded to timepoints from 380 ms onwards. The minimal explanatory power of the contextual models was surprising given that prior studies have found that observers are highly sensitive to violations of object context (Bar, 2004; Biederman et al., 1973; Davenport & Potter, 2004; Ganis & Kutas, 2003; Oliva & Torralba, 2007; Võ et al., 2019). (Mudrik et al., 2010; Mudrik et al., 2014; Quek & Peelen, 2020), and recognise objects more efficiently when they appear alongside related objects (Auckland et al., 2007; Bar & Ullman, 1996; Davenport, 2007; Green & Hummel, 2006; Kaiser et al., 2019; Kaiser et al., 2014; Quek et al., in

press). Given this extensive literature, we would have expected information about objects' contextual associations to be represented (automatically) in the neural response to objects.

One possible explanation for our contradictory finding concerns the overlap in conceptual and contextual features of our selected 190 object concepts. Indeed, although both the Contextual-word and Contextual-image model *did* predict neural responses when considered in isolation (i.e., without other models as covariates), they lost most of their explanatory power when the conceptual model from the same modality was included as a covariate. Previous studies have found that the parahippocampal cortex encodes the contextual representation of objects, specifically how certain objects tend to co-occur with one another within a context (Aminoff, Kveraga, & Bar, 2013; Bar, 2004). Martin and colleagues also found in their fMRI-RSA analysis that conceptual representations were activated in parahippocampal cortex when participants were engaged in a task that evoked conceptual features (Martin, Douglas, Newsome, Man, & Barense, 2018). In line with their findings, our results also seem to demonstrate that objects that tend to occur in the same context often share many conceptual features but can be visually distinct (*e.g.,* a toothbrush and toothpaste). Our study also extends this further by demonstrating that in time-resolved whole-brain EEG response to object images, contextual features, whether derived from images or words, were not uniquely processed by the brain on top of conceptual features; rather, they were processed as part of conceptual processing. Another, non-mutually-exclusive possibility is that contextual associations between object concepts are represented most strongly when two (or more) objects are encountered simultaneously (as has often been the case in prior studies examining contextual relations between objects). Future studies

seeking to disentangle the neural timecourse of contextual object knowledge from its perceptual and conceptual counterparts might exploit such multi-object processing paradigms (Quek & Peelen, 2020; Quek et al., in press), in which the strength of conceptual and contextual object associations could be strictly orthogonalised.

Conclusion

Our study demonstrates the brain's robust and cascaded integration of perceptual and conceptual features in forming object representations. Using RSA to correlate EEG responses with behavioural models, we found that perceptual features dominate early neural responses, while conceptual features emerge later. These findings were consistent across different behavioural task modalities and EEG datasets. Notably, although contextual associations between objects did meaningfully predict the structure of neural object representations, this explanatory power overlapped significantly with models of conceptual object features. By using functionally relevant models of different object dimensions, this work provides insight into how these dimensions are generally represented when observers look at objects. Together, these findings contribute to our understanding of the brain's dynamic processing of visual objects.

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